

## OPTIMUM DESIGN OF COMPOSITE OPEN CHANNELS USING CHARGED SYSTEM SEARCH ALGORITHM\*

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**Abstract**– Composite open channel structures are an expensive infrastructure in terms of material, construction and maintenance, and therefore finding the optimum design becomes an important issue. This paper develops four different models for composite open channel and applies a new optimization algorithm to determine the optimal design of these models. The new algorithm called Charged System Search (CSS) is inspired by the governing laws from electrostatics physics and mechanics. CSS is a multi-agent approach and each agent is a Charged Particle (CP) which can affect others based on their fitness values and their separation distances. The results of the CSS are compared to those of ant colony optimization and the genetic algorithm method to highlight its superiority for determining the optimum design of composite open channel structures.

**Keywords**– Composite open channels, optimum design, minimum cost, charged system search

### 1. INTRODUCTION

Open channel structures are built to convey water for irrigation, city water supply, water power development, drainage or flood control and many other purposes. Due to the high construction costs for these structures, determining the optimum design of channel sections has been an interesting subject in the field of engineering optimization problems.

The first works for determining the optimum design of these structures are limited to the use of some mathematical approaches [1, 2]. Sequential quadratic programming (SQP) is utilized by Bhattacharjya [3] to find the optimum model incorporating the critical flow condition of the channel. Lagrange's undetermined multiplier approach, as another classic algorithm is employed by Chahar [4] to obtain optimal parameters corresponding to the minimum area section and the minimum seepage loss section.

The emergence of meta-heuristic optimization techniques has opened a new era in obtaining the solution of optimization problems, [5-7]. These methods have attracted a great deal of attention, due to their high potential for modeling engineering problems in environments which have been resistant to solution by classic techniques. These approaches do not require gradient information and possess better global search abilities than the conventional optimization algorithms [8]. A genetic algorithm-based method as one of the well-known meta-heuristics was presented by Bhattacharjya and Satish [9] to calculate the stable cost effective dimension of a trapezoidal channel section. Jain et al. [10] optimized composite channels using genetic algorithm, and ant colony optimization as a discrete meta-heuristic algorithm is applied for the design of channels [11, 12].

Recently, a novel meta-heuristic algorithm known as Charged System Search (CSS) was introduced by Kaveh and Talatahari [13], and applied to different engineering optimization problems [14-16]. CSS

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utilizes the governing Coulomb and Gauss's laws from electrostatics and the Newtonian laws of mechanics. Each agent in CSS, called Charged Particle (CP), is considered as a charged sphere. An agent inserts electric force to other agents according to the Coulomb and Gauss's laws. The resultant forces and the laws of motion determine the new location of the CPs. We believe this paper to be the first application of the CSS algorithm in hydraulic and hydrologic engineering aspects.

The present study presents four different models for optimum design of composite channels. In the first model, an equivalent roughness coefficient is computed without any section division. In the second model, the channel section is divided into multi segmental areas by drawing vertical lines and considering a constant velocity for each segment. Consequently, due to different roughness coefficients of the different segments, the horizontal spatial variation of the velocity across the channel section can be handled. The third model, in addition to using three segments similar to the second model, controls the maximum velocity of each segment in order to safely convey the required discharge. The fourth model divides the channel into horizontal slices.

The remaining part of the paper is organized as follows: Section 2 presents the formulation for optimal design of composite channel cross section. Section 3 overviews the CSS algorithm. Section 4 provides the results and discussion of the models. Finally, Section 5 presents the concluding remarks.

## 2. FORMULATION OF THE OPTIMAL DESIGN OF COMPOSITE CHANNELS

Composite open channels are constructed with distinctly different materials for the bed and sides in order to overcome the execution problems and to save costs. For such channels, the roughness along the wetted perimeter may distinctly differ from one part to another part of the perimeter. In composite open channels, the cross section design is generally based on the one-dimensional analysis of steady flow in which the composite roughness is conventionally expressed in an equivalent form [11]. For example, Aksoy and Altan-Sakarya [17] used Manning's formula for determining the optimum channel design. Das [18, 19] employed Horton [20] and Einstein [21] equations for estimating the equivalent roughness in optimal design of a trapezoidal cross. Bhattacharjya and Satish [9] applied Horton's equivalent roughness. In addition, Jain et al. [10] followed Lotter's [22] method which allows spatial variation in segmental velocities across a composite channel section. The latter approach is also adopted in the present paper.

Figure 1 shows the geometry of a trapezoidal channel cross section with different Manning roughness coefficient values  $n_1$ ,  $n_2$  and  $n_3$  at two sides and the bed of the channel. The slopes of side faces having Manning roughness coefficient values  $n_1$  and  $n_2$ , are  $z_1$  and  $z_2$ , respectively. The design variables consist of the bed width  $b(=x_1)$ , the flow depth  $h(=x_2)$ ,  $z_1(=x_3)$  and  $z_2(=x_4)$ . In this figure,  $T_f$ ,  $T_w$  and  $f$  are the top width of the channel cross section, the top width of flow and the freeboard, respectively.

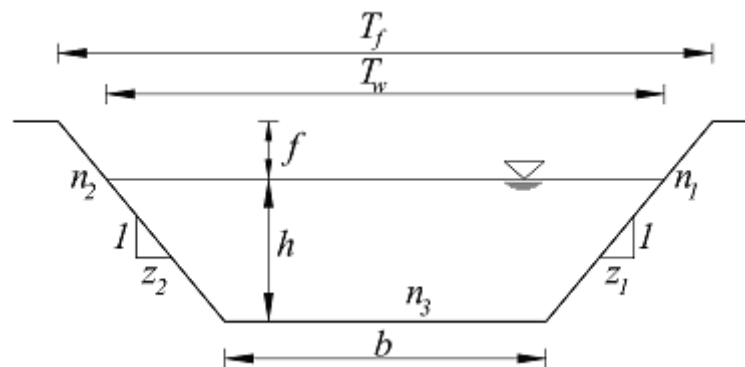


Fig. 1. Composite trapezoidal channel geometry for Model I

The cost function ( $f_{cost}$ ), the total construction cost per unit length of the channel, includes excavation of the cross-sectional area and lining of the side slopes and the bed costs. This function can be written as

$$f_{cost}(\mathbf{X}) = c_1 A_t + c_2 P_1 + c_3 P_2 + c_4 P_3 \quad (1)$$

where,  $A_t$  is the total area, and  $P_1$ ,  $P_2$  and  $P_3$  are the perimeters of side slopes and bed of the channel cross section including freeboard, and can be expressed as

$$\begin{aligned} A_t &= b(h + f) + (z_1 + z_2) \frac{(h + f)^2}{2} \\ P_1 &= \sqrt{1 + z_1^2} (h + f) \\ P_2 &= \sqrt{1 + z_2^2} (h + f) \\ P_3 &= b \end{aligned} \quad (2)$$

And  $c_1$  is the excavation cost per unit area.  $c_2$ ,  $c_3$  and  $c_4$  are lining costs per unit length of the perimeters of the two sides having slopes  $z_1$  and  $z_2$  and perimeter of bed, respectively.

The Manning's equation for a uniform flow, as expressed by Das [18], is the equality constraint (Model I)

$$\frac{Q n_e}{\sqrt{S_o}} - \frac{A_w^{5/3}}{P_w^{2/3}} = 0 \quad (3)$$

where  $Q$  is the design discharge;  $S_o$  is the channel's longitudinal bed slope;  $A_w$  is the wetted flow area;  $P_w$  is the wetted perimeter and  $n_e$  is the equivalent roughness that can be expressed as

$$n_e = \left[ \frac{((1 + z_1^2)^{1/2} n_1^{3/2} + (1 + z_2^2)^{1/2} n_2^{3/2}) h + b n_3^{3/2}}{P_w} \right]^{2/3} \quad (4)$$

In the second model (Model II), as Jain et al. [10] assumed, the cross section of a trapezoidal channel may be divided into three segments, two triangular and one rectangular segment, Fig. 2.

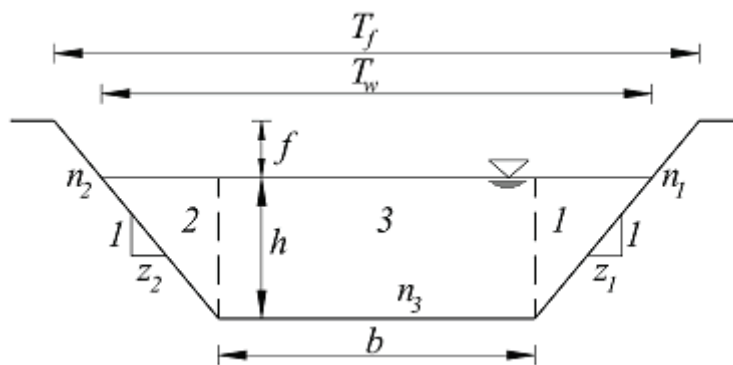


Fig. 2. Composite trapezoidal channel cross section divided into three segments for Models II and III

Each part has a different mean velocity and the sum of segmental discharges is equal to the total discharge. Therefore, the constraint for this model can be expressed as the following [10]

$$\frac{Q}{\sqrt{S_o}} - \frac{A_{w_1}^{5/3}}{n_1 (\sqrt{1 + z_1^2} h)^{2/3}} - \frac{A_{w_2}^{5/3}}{n_2 (\sqrt{1 + z_2^2} h)^{2/3}} - \frac{A_{w_3}^{5/3}}{n_3 b^{2/3}} = 0 \quad (5)$$

where,  $A_{w_1}$  and  $A_{w_2}$  are the wetted areas of the triangular segments and  $A_{w_3}$  is the wetted area of the rectangular segment. These parameters can be written as

$$\begin{aligned} A_{w_1} &= \frac{z_1 h^2}{2} \\ A_{w_2} &= \frac{z_2 h^2}{2} \\ A_{w_3} &= bh \end{aligned} \quad (6)$$

The maximum permissible velocity constraint has been ignored by the presented optimization formulations in the previous models. However, in order to safely convey the required discharge through a composite channel, it is necessary to ensure that the velocity in each segment of the channel not exceed the corresponding maximum permissible velocity which is related to the roughness coefficient of that segment. Modifying the Model II by adding such new constraints resulted in the formation of Model III. For this purpose, in addition to the Eq. (5), three other constraints must be considered to satisfy the velocity limitation in the three segments of the composite channel (Model III), as

$$\begin{aligned} V_1 &\leq V_{1,\max} \\ V_2 &\leq V_{2,\max} \\ V_3 &\leq V_{3,\max} \end{aligned} \quad (7)$$

in which we have

$$\begin{aligned} V_1 &= \frac{\sqrt{S_o}}{n_1} (R_1)^{2/3} \\ V_2 &= \frac{\sqrt{S_o}}{n_2} (R_2)^{2/3} \\ V_3 &= \frac{\sqrt{S_o}}{n_3} (R_3)^{2/3} \end{aligned} \quad (8)$$

$V_{1,\max}$ ,  $V_{2,\max}$  and  $V_{3,\max}$  are maximum permissible velocities in segments 1, 2 and 3 of the composite channel, respectively, and the R's are the hydraulic radius of the three sections, e.g.  $R_i = A_i/P_i$ .

Finally, in the last proposed model (Model IV), to determine optimal dimensions of a composite channel, the virtual horizontal lines with equal distance ( $y_o$ ) from each other are considered dividing the cross section of the channel into horizontal subsections as shown in Fig. 3. The total discharge through the channel cross section in this model can be calculated by

$$Q = \sum_{i=1}^{ns} u_i A_i \quad (9)$$

where  $ns$  is the total number of subsections and  $u_i$  is the velocity with logarithmic distribution at gravity center of subsection  $i$ . In hydraulically rough flows, within a turbulent boundary layer, the vertical velocity profile for the clear water is approximately logarithmic and can be expressed as

$$u = 2.5u^* \ln \frac{30y}{k} \quad (10)$$

where  $y$  is the distance from the bed,  $k$  is the Strickler hydraulic roughness and  $u^*$  is the shear velocity that can be given by

$$u^* = \sqrt{gRS_o} \tag{11}$$

here,  $R$  is the hydraulic radius and  $S_o$  is the energy slope that is equal to the bed slope in uniform flow. Therefore for  $u_i$ , we have

$$u_i = 2.5\sqrt{gR_iS_o} \ln \frac{30y_i}{k_i} \tag{12}$$

in which,  $y_i$  is the distance between the bed and the gravity center of trapezoidal subsection  $i$

$$y_i = (i-1)y_0 + \frac{y_0}{3} \left( \frac{3b + (3i-1)(z_1 + z_2)y_0}{2b + (2i-1)(z_1 + z_2)y_0} \right) \tag{13}$$

In Eq. (9),  $A_i$  is the area of subsection that can be expressed as

$$A_i = \left( b + (2i-1)\left(\frac{z_1 + z_2}{2}\right)y_0 \right) y_0 \tag{14}$$

As a result, the constraint will be

$$\frac{Q}{\sqrt{S_o}} - \sum_{i=1}^{ns} \left( \sqrt{gR_i} A_i 2.5 \ln \frac{30y_i}{k_i} \right) = 0 \tag{15}$$

in which,  $R_i$  is the hydraulic radius at subsection  $i$  and it is equal to

$$R_i = \frac{A_i}{b + (\sqrt{1+z_1^2} + \sqrt{1+z_2^2})y_0} \quad \text{for } i = 1$$

$$R_i = \frac{A_i}{(\sqrt{1+z_1^2} + \sqrt{1+z_2^2})y_0} \quad \text{for } i = 2, 3, \dots, ns$$
(16)

In this model, to estimate an equivalent Manning roughness value for each subsection the Horton's equation that is expressed by Eq. (4) can be used and the Strickler hydraulic roughness  $k_i$  is related to Manning roughness coefficient  $n_i$  as follows [23]

$$n_i = 0.0342k_i^{1/6} \tag{17}$$

Thus, the hydraulic roughness  $k_i$  for each subsection can be calculated as

$$k_i = \left( \frac{1}{0.0342} \right)^6 \left[ \frac{((1+z_1^2)^{1/2} n_1^{3/2} + (1+z_2^2)^{1/2} n_2^{3/2})y_0 + bn_3^{3/2}}{((1+z_1^2)^{1/2} + (1+z_2^2)^{1/2})y_0 + b} \right]^4 \quad \text{for } i = 1$$

$$k_i = \left( \frac{1}{0.0342} \right)^6 \left[ \frac{((1+z_1^2)^{1/2} n_1^{3/2} + (1+z_2^2)^{1/2} n_2^{3/2})y_0}{((1+z_1^2)^{1/2} + (1+z_2^2)^{1/2})y_0} \right]^4 \quad \text{for } i = 2, 3, \dots, ns$$
(18)

Using Model IV, it is possible to obtain the results for a channel when Manning roughness coefficients over the side slopes are variable. Therefore,  $n_i$  can be different for the subsections.

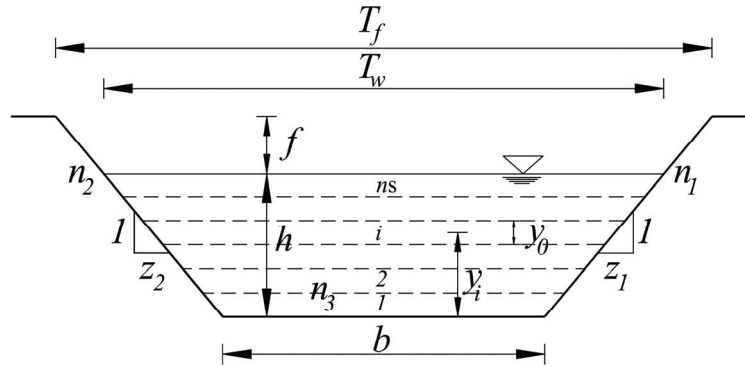


Fig. 3. Composite trapezoidal channel cross section divided into horizontal subsections (Model IV)

### 3. CHARGED SYSTEM SEARCH

The Charged System Search contains a number of Charged Particles (CPs) where each one is treated as a charged sphere and can insert an electric force to the others. The pseudo-code for the CSS algorithm is summarized as follows [13]:

- **Step 1: Initialization.** The magnitude of charge for each CP is defined as

$$q_i = \frac{fit(i) - fitworst}{fitbest - fitworst} \quad i = 1, 2, \dots, N \quad (19)$$

where  $fitbest$  and  $fitworst$  are the best and the worst cost function of all the CPs;  $fit(i)$  represents the amount of cost function of the agent  $i$  and is calculated using Eq. (1); and  $N$  is the total number of CPs. The separation distance  $r_{ij}$  between two charged particles is defined as follows:

$$r_{ij} = \frac{\| \mathbf{X}_i - \mathbf{X}_j \|}{\| (\mathbf{X}_i + \mathbf{X}_j) / 2 - \mathbf{X}_{best} \| + \varepsilon} \quad (20)$$

where  $\mathbf{X}_i$  and  $\mathbf{X}_j$  are the positions of the  $i$ th and  $j$ th CPs, respectively,  $\mathbf{X}_{best}$  is the position of the best current CP, and  $\varepsilon$  is a small positive number. The initial positions of CPs are determined randomly.

- **Step 2: CM creation.** A number of the best CPs and the values of their corresponding cost functions are saved in the Charged Memory (CM).
- **Step 3: The probability of moving determination.** The probability of moving each CP toward the others is determined using the following function:

$$p_{ij} = \begin{cases} 1 & \frac{fit(i) - fitbest}{fit(j) - fit(i)} > rand \text{ or } fit(j) > fit(i) \\ 0 & \text{otherwise} \end{cases} \quad (21)$$

- **Step 4: The force type determination.** In order to improve the exploration rate, not only attractive forces but also repelling ones are utilized in the algorithm using a parameter so-called the force type defined as [24]

$$ar_{ij} = \begin{cases} +1 & rand \leq 0.8 \\ -1 & rand > 0.8 \end{cases} \quad (22)$$

where  $ar_{ij}$  determines the type of the force, where +1 represents the attractive force and -1 denotes the repelling force,  $rand$  is a random number generated in the range (0, 1). In general the attractive force collects the agents in a part of search space and the repelling force strives to disperse the agents.

- **Step 5: Forces determination.** The resultant force vector for each CP is calculated as

$$\mathbf{F}_j = q_j \sum_{i,i \neq j} \left( \frac{q_i}{a^3} r_{ij} \cdot i_1 + \frac{q_i}{r_{ij}^2} \cdot i_2 \right) ar_{ij} p_{ij} (\mathbf{X}_i - \mathbf{X}_j), \quad \begin{cases} j = 1, 2, \dots, N \\ i_1 = 1, i_2 = 0 \Leftrightarrow r_{ij} < a \\ i_1 = 0, i_2 = 1 \Leftrightarrow r_{ij} \geq a \end{cases} \quad (23)$$

Here, each CP is considered as a charged sphere with radius  $a$ , which has a uniform volume charge density. In this paper, the magnitude of  $a$  is set to unity, however, for more complex examples, the appropriate value for  $a$  must be defined considering the largeness of the search space [13].

- **Step 6: Solution construction.** Each CP moves to the new position as

$$\mathbf{X}_{j,new} = rand_{j1} \cdot k_a \cdot \mathbf{F}_j + rand_{j2} \cdot k_v \cdot \mathbf{V}_{j,old} + \mathbf{X}_{j,old} \quad (24)$$

$$\mathbf{V}_{j,new} = \mathbf{X}_{j,new} - \mathbf{X}_{j,old} \quad (25)$$

where  $k_a$  and  $k_v$  are the acceleration and the velocity coefficients, respectively; and  $rand_{j1}$  and  $rand_{j2}$  are two random numbers uniformly distributed in the range (0, 1).

The effect of the previous velocity and the resultant force affecting a CP can decrease or increase based on the values of the  $k_v$  and  $k_a$ , respectively. Excessive search in the early iterations may improve the exploration ability; however, it must be decreased gradually. Since  $k_a$  may be treated as a controller of the exploitation, choosing an incremental function can improve the performance of the algorithm. Also, the velocity coefficient  $k_v$  may control the exploration process and a decreasing function can be selected. Therefore,  $k_v$  decreases linearly from 0.5 in the first iteration to zero in the final iteration, while  $k_a$  increases from 0.5 to one when the number of iterations rises.

- **Step 7: CP position correction.** If each CP swerves off the predefined bounds, its position is corrected using the harmony search-based handling approach as described in Ref. [8].
- **Step 8: CM updating.** The better new vectors are included in the CM and the worst ones are excluded.
- **Step 9: Terminating criterion control.** Steps 3-8 are repeated until a terminating criterion is satisfied.

#### 4. RESULTS AND DISCUSSION

The model parameters in this study have been adopted as used by Das [18] and Jain et al. [10], as identified in Table 1. Also, the required parameters for the CSS algorithm are presented in Table 1.

Table 1. Modeling parameters of the trapezoidal channel

Flow factors			Manning coefficients			Cost function parameters			
$(\text{m}^3/\text{s}) Q$	$(\text{m}) f$	$S_0$	$n_1$	$n_2$	$n_3$	$c_1$	$c_2$	$c_3$	$c_4$
100	0.5	0.0016	0.018	0.020	0.015	0.60	0.25	0.20	0.30
Maximum velocities (m/s)			CSS parameters						
$V_{1,\text{max}}$	$V_{2,\text{max}}$	$V_{3,\text{max}}$	$N$	$a$	$k_a$	$k_v$	$\varepsilon$		
1	2	3.5	20	1	0.5~1	0.5~0	1.0E-6		

Table 2 compares the results of the CSS method with those of the ACO and GA algorithms for the two first models. In this table, the results of Models I and II for GA have already been reported by Jain et al. [10]. Also, Nourani et al. [11] as well as Kaveh and Talatahari [12] utilized the ACO method to solve the channel optimization. For the first model, the CSS and improved ACO [12] find the best results, while the next results belong to the standard ACO [11] and the GA [10]. For the second model, the value of the best cost function for the CSS algorithm is 14.415, while it is equal to 14.646, 14.888, and 15.089 for the improved ACO, ACO and GA, respectively. In order to have a statistical study, this model is solved 50 times and the results are compared to those of the previous studies. In a series of 50 runs, the average cost function of the CSS is 15.36 and the worst cost function is 16.42 with a standard deviation of 0.47, while the average cost function of ACO [11] is 15.88 and the worst cost function is 16.94 with a standard deviation of 0.65; the average cost function of GA [11] is 19.30 and the worst cost function is 23.21 with a standard deviation of 2.17. Figure 4 compares the final results of the CSS, ACO and GA in 50 runs for Model II. The results of the GA and ACO were presented in [11]. This figure shows that the CSS algorithm is more stable than ACO and GA and, as a result, it is a more reliable algorithm which can be used easily to determine the optimum design of channel sections.

Table 2. Optimum results for trapezoidal channels design (Models I and II)

Methods	<i>Optimal design variables</i>					Model
	$x_1(b)$	$x_2(h)$	$x_3(z_1)$	$x_4(z_2)$	$f_{\text{cost}}$	
GA [10]	5.433	4.211	0.272	0.296	22.973	I
ACO [11]	5.845	4.045	0.244	0.265	22.961	I
Improved ACO [12]	5.874	4.047	0.237	0.256	22.958	I
<i>Present study</i>	5.863	4.038	0.236	0.270	22.958	I
GA [10]	3.539	4.037	0.244	0.131	15.089	II
ACO [11]	3.690	3.959	0.116	0.198	14.888	II
Improved ACO [12]	3.789	3.919	0.1272	0.122	14.646	II
<i>Present study</i>	3.537	4.079	0.114	0.133	14.415	II

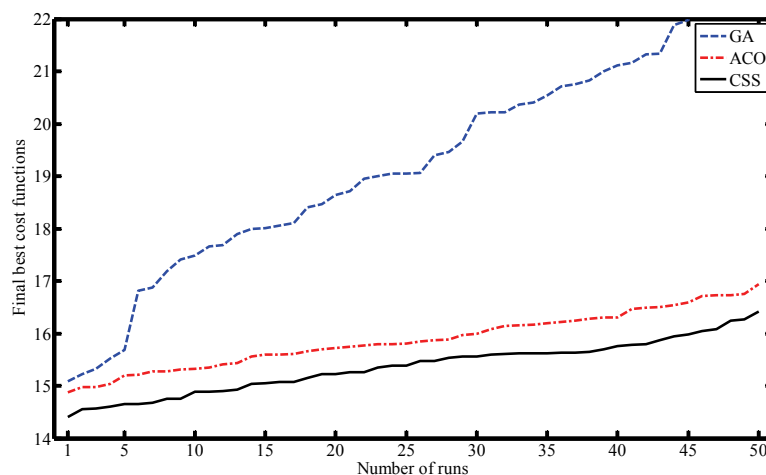


Fig. 4. Final results in 50 runs for Model II

The results obtained for Model III are presented in Table 3. It is also shown that though the cost function is increased, compared to the Models I and II, the segments velocities are all within the allowed ranges. Therefore, this model can be considered as a better one compared to the previous ones when designing a safe channel becomes important. Ignoring the condition of a safe channel may cause unexpected defects when using the channel. For example, for erodible channels, the constraint of maximum permissible velocity must be considered, while for non-erodible channels it has less importance.



Therefore, the main aim of Model III is to design an economical channel, but it must be useable in the defined lifetime considering the utilized material, construction and service conditions.

Table 3. Optimum results for trapezoidal channels design (Model III)

Parameters	GA [10]	ACO [11]	Present study
$b$ (m)	19.200	19.138	19.066
$h$ (m)	1.492	1.488	1.499
$z_1$	0.200	0.125	0.211
$z_2$	0.200	0.122	0.119
$A_1$ (m <sup>2</sup> )	0.397	0.139	0.237
$A_2$ (m <sup>2</sup> )	0.397	0.135	0.134
$A_3$ (m <sup>2</sup> )	38.240	28.737	28.576
$V_1$ (m/s)	0.555	0.449	0.576
$V_2$ (m/s)	0.617	0.449	0.443
$V_3$ (m/s)	3.482	3.479	3.439
$f_{\text{cost}}$ (units)	30.09	30.023	29.893

Velocity constraints in Model III limit the domain of the water depth where it has not been allowed to take a value more than a certain magnitude which, for the case study at hand, is found to be 1.5 m. The best result found by CSS is 29.89, while it is 30.02 and 30.09 for the ACO and GA algorithms, respectively

The last model which is investigated in this paper contains the virtual horizontal lines with equal distance dividing the cross section of a channel into horizontal subsections. Fig. 5 shows the amount of the cost function for this model with various numbers of subsections. When the number of subsections increases, the amount of cost function decreases; however, it is expected that ultimately this converges to a certain value. In fact this model presents a finite element model of a channel section. Computational cost and accuracy of results are two points that determine the number of subsections. Ignoring the importance of this, it is expected that after a determined value for the number of subsections, the cost function will asymptote to a definite value.

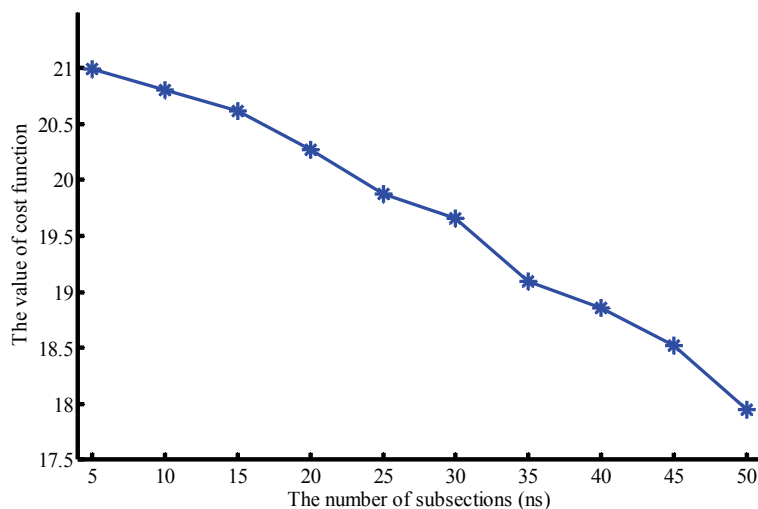


Fig. 5. The value of the cost function related with the number of horizontal subsections

## 5. CONCLUDING REMARKS

Charged System Search (CSS) as a new optimization algorithm is presented to determine the optimum design of composite open channel sections. This algorithm starts by defining the parameters of the algorithm, the primary location and velocity of the CPs, and a memory to store the best CPs. Then in the search level, each CP moves toward the others considering the probability function and the kind and magnitude of the resultant force vector. This algorithm utilizes the governing laws from electrostatics to determine the resultant force vector and the Newtonian laws of mechanics to specify the movement of CPs.

For channel optimization design, four models are proposed. As some previous studies, Models I and II utilize the uniform velocity in the cross section or sub-sections to reach an optimum design, respectively. In the third model, the flow discharge equation and the maximum permissible velocity have been used as the model's constraints which can obtain a safe design compared to the two previous models. However, its cost function is large. Therefore, using the logarithmic velocity distribution with depth for open channel flow, Model IV is introduced. Considering logarithmic velocity distribution is not only more appropriate according to the boundary layer theory, but also it presents a more realistic simulation for the channel sections, especially when a large number of segments is selected. In addition, this model provides an economical design compared to Model III. This model may be used when the Manning coefficients over lateral sides of the channel are not constant. In some countries which do not have advanced compaction equipment to reach to a constant Manning coefficient in the lateral sides, the use of this model can be recommended. Although here it is assumed that the Manning coefficient is constant over the bed and the two lateral sides, this model can use different Manning coefficients for different subsections.

Comparing the results of the charged system search, ant colony optimization and genetic algorithm show the efficiency of the new approach in open channel optimal design. To sum up, it is expected that this algorithm can be utilized in the other field of water optimization problems due to its good capability in solving these problems.

The future works not only must focus on expanding the CSS to the other optimization problems of the field of hydraulic and hydrologic engineering, but they can also investigate other models of channel design. One suggestion is to add thickness for the bottom lining, and the side linings as variables to the cost function in which the area cost will be referred to as the excavation costs and that an additional cost be added as a right-of-way cost. By considering some additional constraints such as the amount of the wastage discharge, the thickness variables become computable. The practical reason for including the right-of-way costs separated from the excavation costs is that often these costs may be the dominate costs if the channel passes through very costly real estate, such as through cities. Using this complex, but complete cost function may provide more practical and realistic designs.

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